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Evidence for a Short-Period Internal Clock in Humans

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Abstract—The concept of an internal clock in humans and animals has had many supporters and detractors over the years. In this article, we demonstrate the apparent existence of an extremely precise time sense in humans, but the process is not related to conscious estimates of the passage of time. Instead, the experiments indicate that there is a mechanism, operating below the level of consciousness, that, with occasional feedback, can keep track of clock time. The precision of the system is quite extraordinary; the observations are consistent with synchronization between the internal timekeeper and clock time to within an averaged value of one part in 10^4.

Introduction

Time estimation experiments are generally classifiable into two groups—those in which various aspects of the circadian rhythm are studied, and those in which abilities to estimate shorter (ultradian) time periods under various circumstances are investigated. Circadian rhythm studies tend to be experiments conducted without feedback, since it is the free-running frequencies that are sought. Ultradian studies may include feedback, to enable subjects to improve their performance.

One of the puzzling observations about circadian rhythms is the discrepancy between the natural 24-hour cycle and the period that develops when environmental clues are removed (Aschoff, 1981; Moore-Ede, Sulzmann, & Fuller, 1982). Experiments with humans and animals show that very precise free-running periods are established, although generally distinctly different from the 24-hour period, often by several hours. Of what benefit is the capability to measure 27-hour periods with a precision of a few minutes, as has been observed in laboratory studies? If one can succeed in demonstrating the usefulness to an organism of having a free-running period longer than the natural one, would this explanation also hold for the cases where the period is much shorter than 24 hours?

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The present study is one for which there is little precedent. Time estimation is carried out unconsciously, with the task, set by the "mind" itself, being to stay synchronized to an external clock. How this is done, and perhaps more importantly, why it is done, is far from clear. Conceptually, it may be akin to the circadian rhythm studies, but occupies a much higher frequency domain.

The genesis of these experiments was an observation by the author, using a digital watch, that there appeared to be a strong tendency to look at the time just at the change of minutes. That is to say, the typical "seconds" reading would be 55-04. An a ***priori*** prediction for the results of such an experiment is surely that the seconds reading should be randomly distributed from 00 to 59. Thus, the observations suggest that there is a bias in the system. Extensive studies were subsequently carried out to locate this apparent bias, and that is the topic of this article. The principal subject is the author, but midway through the experiments two other subjects were accidentally located, who were making the same observations independently.

Results

The basic experiment is extremely simple. The subject merely writes down the time that he observes when he consults his watch throughout the day, with emphasis on the "seconds" reading. Each reading must be recorded, and as the subject becomes used to writing down the data it becomes a routine. Ideally, he does not find himself looking at his watch more than usual.

A variety of experiments were carried out, to attempt to understand the nature of the phenomenon, and to determine whether it was merely an observational artifact. To establish typical results, the most basic protocol was to write down watch readings, day after day, for several months. Data were not taken every day, but once started in the morning, all data were recorded the rest of the day.

In Figure 1 are presented the results of 5 months of data acquisition, totalling 1489 watch readings. Both actual points and 3-point averaged smoothing of the histogram are shown. The peaking around 00 is very striking, as is the symmetry of the distribution. A χ^2 test, assuming an expected random distribution, indicates that the probability that this is the case is 2×10^{-15}. This number is sufficiently small that we need not dwell on the possibility that the effect is due to chance—it is either a real phenomenon, or there is a bias in the way the data are taken.

In Figure 2 the data for individual days are displayed, showing the distribution of days having particular fractions of readings in the 55-04 second range. For the 39 days on which readings were taken, there is only one for which the fraction is lower than the chance value, 0.167, and the maximum value is 0.45.

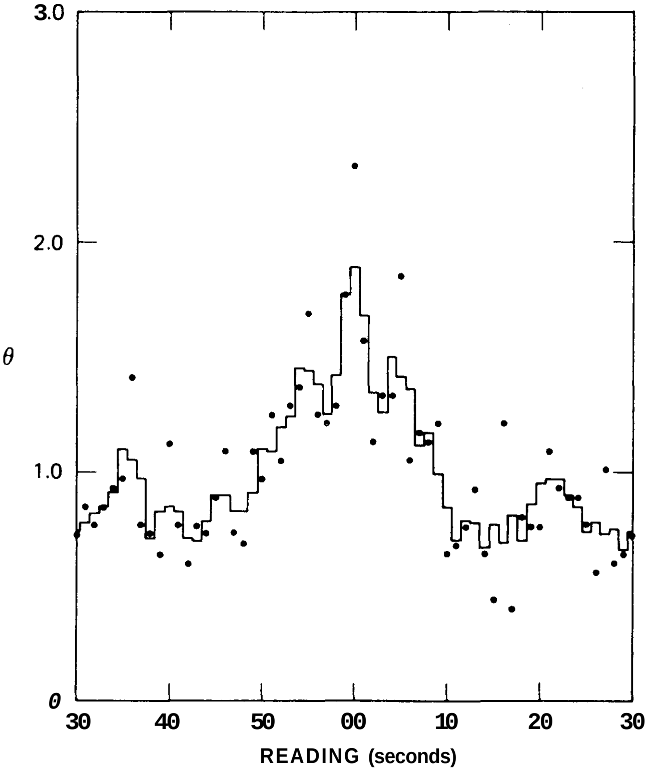

Fig. 1. Frequency distribution (TGS), 1489 points. Ordinate is normalized frequency, θ = (60/1489)r, where r is total number of readings (dots) or readings smoothed by Σ (r ± 1)/3 (line).

There are basically two potential data collection problems. One possibility is that if the subject has a preconceived idea of the desired experimental outcome, then he may consciously or subconsciously choose to ignore a sufficient number of "unsatisfactory" readings so that the data show the desired result. It seems more reasonable to assume that "unsatisfactory" readings might be ignored than that "satisfactory" readings would be invented. It is presumed that any data manipulation is unconscious.

A second issue is that the data may be valid, but not related to time estimation. For example, if digital watches give out a subliminal EM or audio signal at the change of minutes, then conceivably the subject might respond by looking at his watch. In this case, the data would exhibit a threshold at 00.

An essential part of any scientific study is to determine what parameters are related, that is, how can the observed outcome be changed. The results of Figure 1, taken at face value, suggest that, in anthropomorphic terms, there is an internal timekeeper that occasionally requests a time check. It has

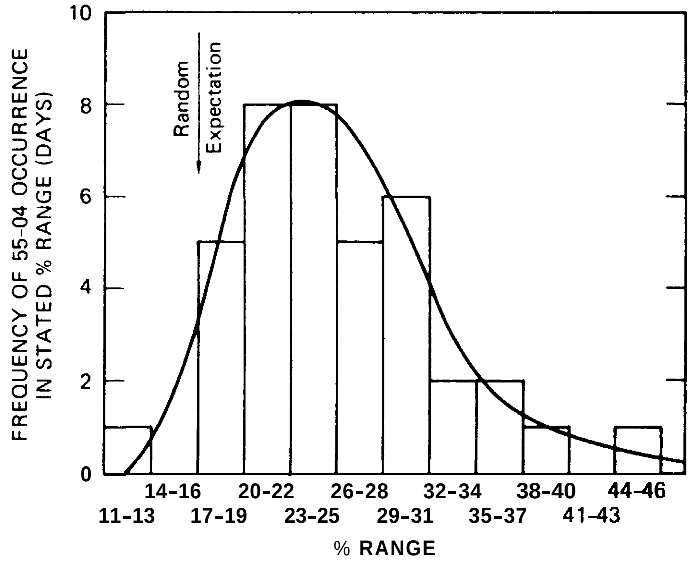

Fig. 2. Observed daily percentage occurrence of seconds within the range 55-04, 39 days (TGS).

chosen to synchronize itself to the watch, and finds that for the purpose of feedback, a 00 reading is more acceptable than an arbitrary number.

Since the 60-second period is a human construct, and a relatively recent one, it is not reasonable to suppose that it is a period natural to humans, as is 24 hours (in spite of the fact that the free-running period is more typically 25 hours). Therefore, it must be presumed that the timekeeper has adjusted its period to that of the watch. If that is so, there is an obvious question that arises. What is the effect of changing the period and phase of the watch? If there is no effect, it would be consistent with the idea that the watch sends a signal to the wearer at the change of minutes, and that there is no internal timekeeper. If there is an effect which disrupts the phenomenon, it will provide information on the resynchronization time, and will weigh against the idea that the subject is unconsciously manipulating the data.

In order to change the watch period in a sensible manner, an extremely small adjustment is needed. One second per minute, for example, is far too large, since in the average time between readings, 30–40 minutes, the effective period change would be as large as the maximum phase change of 30 seconds. A further reason why such a large change is unsatisfactory is because a watch that loses or gains a half hour a day is useless for telling time, and it is important in these experiments that the natural impulse to consult one's watch be perturbed as little as possible.

A much smaller change is required, and a quartz crystal reject was obtained whose period differed from absolute time by only 1 part in 10^3, gaining 100 seconds per day. In Table 1, data are presented that show the

TABLE 1
Frequency distribution in 6-second intervals (TGS)

Intervals	A	B	C	D	E	F
56–01	234	53	47	41	68	375
02–07	195	39	24	28	63	286
08–13	133	21	30	14	52	198
14–19	109	18	21	25	65	173
20–25	135	30	27	18	71	210
26–31	109	20	20	15	63	164
32–37	141	27	15	28	56	211
38–43	115	29	23	17	73	184
44–49	129	20	19	14	65	182
50–55	189	29	27	29	57	274
Average	149	29	25	23	63	226
N	1489	286	253	229	633	2257
χ^2	108.7	35.9	27.6	30.8	6.4	175.7
p	10^{-19}	3×10^{-5}	8×10^{-4}	2×10^{-4}	0.7	$\ll 10^{-25}$

A. Initial run, 5 months, Figures 1 and 2, standard watch.
B. Run immediately preceding frequency alternations, fast watch.
C. Frequency alternation, fast watch.
D. Frequency alternations, standard watch.
E. Phase shift run, 30-second displacement every 24 hours, standard watch.
F. Sum of runs A–D.

results of these frequency changes. Because of the limited number of readings, the data are collected in 6-second bins. Column **A** shows the results of the initial run, from Figure 1. These data were taken 15–20 months prior to those in Columns **B–D.** Column **B** consists of data taken over a period of one month with the fast watch, demonstrating that a slightly different frequency results in no change in performance. The data in Columns C and **D** were taken with the fast watch and the standard watch, respectively. The watches were switched approximately every day, but at irregular times, and at each switch the new watch was synchronized to the old, so as not to change phase. There is little difference between the results in the three columns; each distribution is seen to differ greatly from chance expectations, and moreover, each peaks near 00. The fraction in each bin for a random distribution should be 0.10. What is observed in the 56–01 second bin for columns **A–D** is, respectively, 0.157, 0.185, 0.186, and 0.179. It therefore appears that the internal timekeeper is not tied to an absolute period, but can adjust easily to a slightly different period. Included in Table 1 are values of χ^2, based on the expectation of a random distribution, and the probability of obtaining such a result by chance.

If a gradual change can be accomodated, is this also true for an abrupt phase change? Column E in Table 1 shows the effect of changing the watch phase by 30 seconds every day, for a period of several weeks. It is evident that the ability to favor readings near 00 has vanished, and that the distribution is now random; the fraction in the 56–01 second bin is 0.107. Whereas the frequency change experiment did not exclude the possibility that the phenomenon was due to a subliminal watch signal, this phase change experiment shows this not to be the case, for detection of such a signal would be independent of phase or period.

The phase shift experiment is quite critical, since it shows that the positive results can be turned on and off. The obvious follow-up experiment is the determination of how long it takes for resynchronization to be achieved. Such experiments are shown in Figure 3, where data were taken before (a)

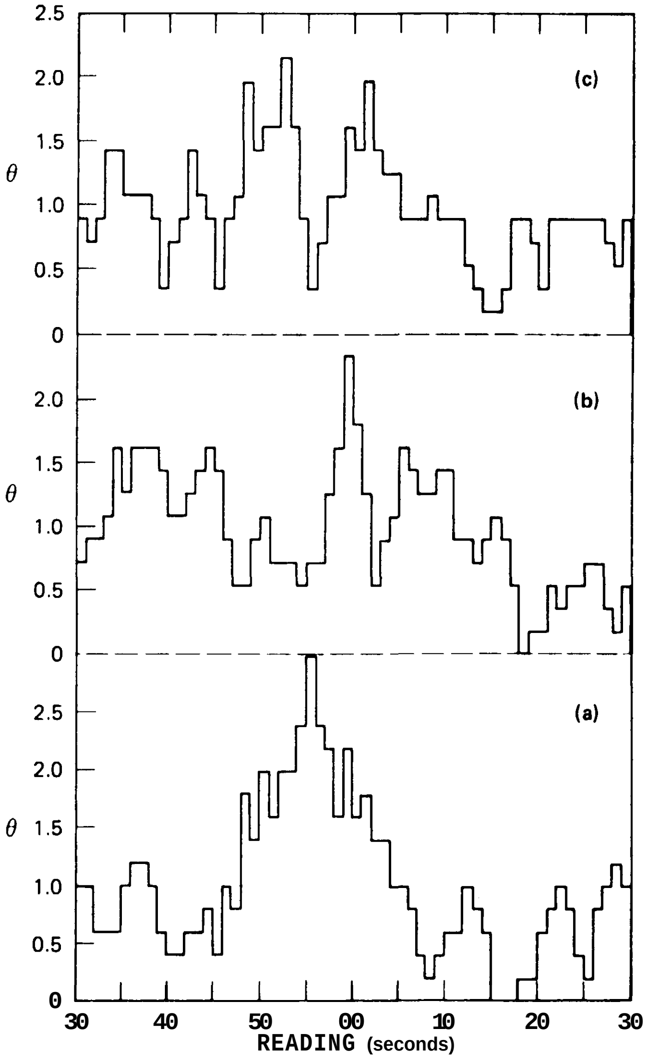

Fig. 3. Frequency distribution (TGS) for 30-second phase shifts. a) 5-day control period, b) 4-day period after shift, c) 4-day period after second 30-second shift.

and after (b) a 30-second phase change. The 5-day control period gave the usual 00 peaking, and after the phase change the data became random. At the end of the four days, 00 peaking started to reappear, which was then suppressed by a second 30-second shift (c). Although not apparent in the figures, immediately after the phase shifts there were indications of peaking around 30. It therefore appears that an abrupt 30-second change destroys the coupling between the watch and the timekeeper, whereas when the same phase change is introduced slowly, over the 8 hours that it took the fast watch to drift 30-seconds, there was no difficulty in following it. The observation that several days are required for resynchronization is consistent with the fact that daily 30-second changes result in chance distributions. There are many mechanical analogs to such a situation, the issue being the tightness in the feedback coupling; the more loosely two system components are coupled, the more difficult it is for the driven component to follow an abrupt change in the driver mode.

When many of these results had already been obtained, and a manuscript circulated, I discovered that one of my colleagues (DRC) had been carrying out the identical experiment, over a period of several months. The reasons were the same—he had seen, on first obtaining a digital watch, that the seconds readings around 00 appeared surprisingly often. Although his observations were not as extensive as my own, the effect was even more pronounced. He had adopted the same protocol, with a conscious bias in that if the first reading of the day was close to 00, he would continue to take readings throughout the day. However, the effect is so strong that the first reading can be ignored with little change in the results.

Of particular interest is the fact that DRC also did a resynchronization experiment. After initially establishing the timekeeping effect with a digital watch, he used an analogue watch for several weeks, then returned to the digital watch and started recording the data. He observed that for a period of 10 days the readings were random, but on the 11th day 00 peaking appeared, and continued for at least 6 months. The synchronized data are plotted in Figure 4, with and without the first reading of the day. In either case, the distribution is more sharply peaked than that of Figure 1. The data are tabulated in Table 2. Column A shows all the synchronized data, while in Column B, the first reading of the day has been excluded. In Column *C* are the data from the 10-day unsynchronized period, clearly showing a random distribution, and for comparison, Column D shows data from a random number table. The fraction of points in the 56–01 second bin for the four columns is 0.240, 0.208, 0.072, and 0.120.

Particularly noteworthy in the experiments of DRC is the fact that he is in the habit of wearing long-sleeved shirts. This assures that it is very unlikely for him to look at the watch in an inadvertent manner—two deliberate actions must be taken to make a reading, pushing up his sleeve and focusing his eyes.

Yet a third subject (PLS) was found, through a mutual acquaintance, who had been carrying out the same measurements for the same reasons. In his

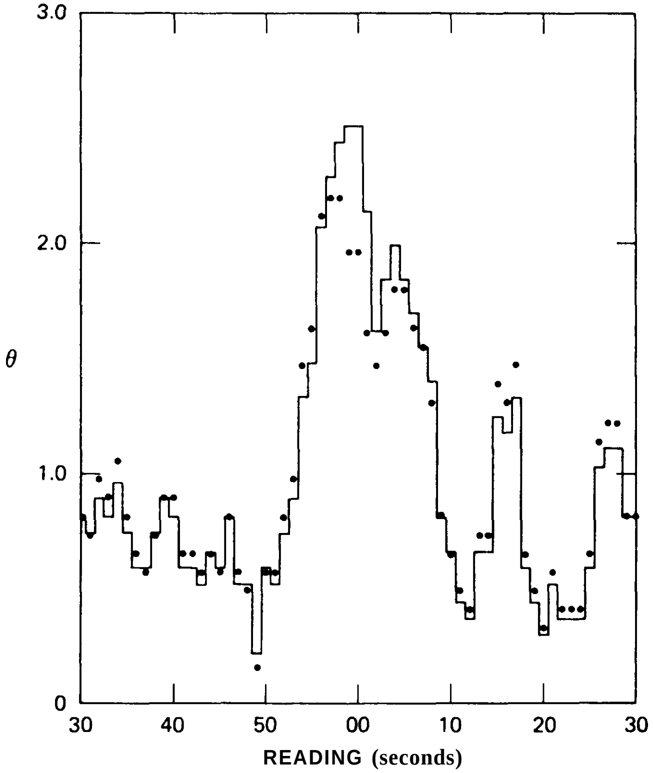

Fig. 4. Smoothed and normalized frequency distribution (DRC), 271 points. Line represents total data, dots represent data excluding first reading of day.

own analysis of his results he suggests that the explanation lies with a watch signal, because the peak appears asymmetric, suddenly rising at 00. This is of course different from the results of the author and DRC, where the peak is symmetric and commences well before 00. PLS also noticed that there would be periods, typically one month, where the effect was strong, and periods where it would vanish. Subsequently, both DRC and the author subjectively confirmed that there are periods of high and low "success" rates. However, the data presented in Figure 1 and Table 1 were taken before this apparent fact was known, and thus there was no bias against "unsatisfactory" months.

It should be noted that these experiments are unique in that any slippage in frequency between the timekeeper and clock time will produce a null result in the experiment. A period of 59.9 seconds accumulates to six seconds per hour, a discrepancy sufficient to accomplish this. It is known that circadian and ultradian rhythms are affected by drugs, diet, and stress (Church, 1984), and thus it is credible to find periods when the effect is indiscernible.

TABLE 2
Frequency distribution in 6-second intervals (DRC)

Intervals	**A**	**B**	C	D
56–01	65	51	14	23
02–07	48	41	28	20
08–13	16	15	22	19
14–19	25	25	12	12
20–25	12	12	25	15
26–31	26	25	20	22
32–37	19	19	27	28
38–43	20	19	17	18
44–49	15	13	13	15
50–55	25	25	16	22
Average	27.1	24.5	19.4	19.4
N	271	245	194	194
χ^2	92.1	57.7	16.1	11.7
p	5×10^{-16}	1×10^{-8}	0.07	0.25

A. After synchronization achieved, all data.
B. First reading excluded.
C. Before synchronization, 10 **days.**
D. **Data from random number table.**

The issue of the feedback requirement is of course of great interest. How often is the information required? The answer would appear to be, not very often. This conclusion is drawn from the fact that there is no feedback at night, yet if one goes to bed synchronized, one wakes up synchronized. Just as important, if one goes to bed unsynchronized, one is not synchronized the next day. Therefore, synchronization persists throughout the night, 3×10^4 seconds, and cannot be induced by the first reading of the morning (the latter point is obvious, since resynchronization takes several days). One may thereby conclude that the system has an averaged precision on the order of one part in 10^4. This figure is consistent with the data of DRC, which were obtained with an average of only 12 readings per day, just half of my own average.

The writer is unaware of any living system that maintains a frequency to that precision, or needs to. Enright (1979) has remarked that observations of free-running circadian periods in house finches and flying squirrels exhibit a precision of one part in 500 (equivalent to a 59.9 second minute), yet the present observations improve on this figure by more than an order of magnitude. Assuming that a chemical system is the basis for the operation of the timekeeper, it must therefore operate in a manner that is rather independent of the environment, and in particular it must be strongly temperature-independent.

A part of this study was carried out during a period when the circadian rhythm of the author was disrupted by ±8 hours, with no obvious effect on the synchronization. Beljan et al. (1972) have shown that the length of time needed to resynchronize the psychomotor performance rhythm after travel across six time zones is several days (cited in Moore-Ede et al., 1982, p. 323). It thus appears that these two phenomena, which differ in frequency by more than three orders of magnitude, are not closely coupled in one sense, yet exhibit very similar resynchronization times when phase shifts comparable to their periods are introduced.

As regards temperature, humans exhibit a circadian rhythm with an amplitude of +1°C (Sweeney & Hastings, 1960). Activation energies of many biological chemical reactions are such that the corresponding reaction rate change is ±10%. Thus, strong temperature compensation must be required for the reactions that determine the operation of the timekeeper.

Discussion

There are three major questions that need to be addressed. Is the interpretation of the data as an indication of an internal timekeeper valid? If so, how does such a process operate? And most important, why should such an ability exist?

In terms of the usual protocol for psychological experiments, the first question can only be answered affirmatively if adequate controls are provided. The nature of the experiment makes this difficult, as the principal subject is the experimenter. Although the discovery of an independent observer making the same observations and reaching the same conclusions is extremely encouraging, it has not yet been possible to carry out a fully controlled experiment.

The reasons for this are complex. This is not a laboratory experiment, and data are only forthcoming at a subject's own pace. A study takes months, and it is necessary for a subject to conscientiously take data, and yet be sufficiently removed from the experiment so that he looks at his watch only to check the time, not to get a data point. The more complicated the protocol, the more aware a subject is of the whole process. The expected need for feedback conflicts with possible control experiments, in which the seconds readings are automatically recorded but not perceived by the subject.

It is for these reasons that the experimenter-as-subject approach has been used. Since neither DRC nor myself had any preconceptions as to results, it is difficult to claim that we have subconsciously fabricated them. It is true enough that 00 is a very symmetric number, and that one might be particularly attuned to its observation. However, to make the data of Figure 1 appear random requires that the 58 00's that were in fact observed (compared to the chance expectation of 25) must be accompanied by 59 × 58 non-00's. In other words, all 00's would have been recorded, but 60% of all readings were unconsciously discarded. I estimate that 5–10% of readings were not recorded, having been made in adverse circumstances (moving vehicles, etc.), but the idea that more than half of them were not recorded is not realistic. Furthermore, such an explanation can hardly rationalize the shapes of the distributions in Figures 1 and 4. It must be noted that one cannot glance at a digital watch as one can an analogue watch; the eyes must focus to register the digits. Furthermore, I had no preconceptions concerning the phase and period shift experiments, yet they gave diametrically opposite results. In spite of the lack of the usual types of controls, I consider the data robust enough to be grounds for further study.

The second question, concerning how such a process might occur, is beyond the expertise of the writer. There is an extensive literature on circadian rhythms, and it has been shown that the suprachiasmatic nuclei in the hypothalamus are an important site of the timekeeping ability in mammals (Groos & Daan, 1985; Moore-Ede et al., 1982). However, there is no basis to claim that the same organ would be involved at the much higher frequencies under consideration here. In fact, there is considerable evidence that even for circadian periods, organisms contain multiple oscillatory systems (Takahashi & Zatz, 1982). Current attempts to explain the mechanism of timing tend to use information-processing models (Gibbon, Church, & Meck, 1984) and a cognitive approach, as opposed to the older internal clock concept.

The how and the why are inextricably linked, for there seems to be no obvious reason why such a remarkable ability should exist, or what would be the evolutionary pressures that would cause it to develop. The ability to measure short intervals of time repetitively and with great precision has no obvious purpose, yet the experiments indicate that it is not only an ability, but that the organism actually **requires** the temporal information. Were this not so, there would be no peaking in Figures 1 and 4, since if the ability existed without the need for synchronization, then the phenomenon would not manifest itself in this way, and would remain unrecognized. The difference between these studies and conscious time estimation experiments should be emphasized. Performance in the latter, for 6-second and 10-second intervals, has been shown to depend on the circadian cycle phase, and is typically of ±10% precision (Poppel & Giedke, 1970).

The principal conclusion of the present experiments is that looking at one's watch may take place at non-random times. The thought of checking the time does not necessarily arise spontaneously, or because one has a schedule to meet. It can arise to satisfy the requirements of the internal timekeeper. In fact, the effect can be quantified, by comparing the random expectations with the non-random observations in Figures 1 and 4. The 00 peaks have a width, measured from the base line, of 20 seconds in Figure 1 and 16 seconds in Figure 4. Since the data and their interpretation lead to the conclusion that the timekeeper itself is very accurate, this width is indicative of a response lag between the command, originating with the timekeeper, and the conscious mind; the data in the 50 → 00 interval would seem to correspond to an anticipatory response. Ignoring the other minor peaks that appear in Figures 1 and 4 (although they may be significant), one interpretation of the data is that during the 10 → 50 second interval the decision to look at one's watch is "consciously" controlled, whereas in the 50 → 10 second interval it is partially controlled by the timekeeper. Treating the data in Figure 1 in this manner, one finds that 40% of the points in the 50 → 10 second range lie above the base line and are therefore due to the timekeeper, and these points represent 19% of the total number. From Figure 4, 65% of the points in the 53 → 09 second range lie above the base line, representing 32% of the total number. Therefore, my own data indicate that four times out of five, the decision to look at my watch is *not* controlled by the timekeeper. The data of DRC indicate that this is true for him two times out of three.

One may well ask how this urge to know the precise time is satisfied in people who don't wear watches; obviously there is at present no answer. If people have "natural" periods on the order of 60 seconds, their utility is as mysterious as the natural non-24-hour circadian periods mentioned earlier. Only by entraining to a watch are these rhythms observed. One might argue that it is well known that the brain tends to process and store a variety of forms of information made available to it, for reasons that we do not understand. A piece of music not heard for 40 years may suddenly be brought back to conscious memory, which means that the temporal structure has remained intact. There may be some relationship between such information processing and the unexpected temporal behavior described here.

It is difficult to place these observations within the framework of current studies of time perception, because they are not task oriented. They represent a sidewards glimpse of a natural process, in that the data are obtained in as passive a manner as possible. It is presumed, although not proven here, that a deliberate attempt to guess when the seconds are close to 00 will not be successful. There are many descriptions of ultradian experiments, involving periods of time of a few seconds. For example, Treisman (1984) has attempted to relate the ability to estimate four-second intervals to a-rhythm frequencies, finding that, over a period of time, the time estimation ability is much more variable than changes in the a-rhythm frequency. It is my belief that the non-conscious aspect of the present experiments may be most reasonably compared with hypnotic and sleep studies. As pointed out by Block (1979), estimation of time duration during sleep involves an unknown subconscious process.

Regarding hypnotic investigations, there is an extensive literature on time perception experiments carried out in the period 1890–1925. There is a tendency for modern researchers to ignore studies of this vintage, but this work provides the closest parallel to the present observations. The experiments, pioneered by Bramwell (1900, 1930) are based on the supposition that there is a class of subjects (somnambules) who can be given suggestions under hypnosis of which they have no waking memory. Bramwell studied several individuals over a number of years, using extensive variations in testing their performance on a single task—the estimation of a period of time told to them while under hypnosis. For example, the subject would be told to make a mark on a piece of paper in 9278 minutes, and would be observed to do so at the appropriate time with surprising accuracy, and with no comprehension of why she was doing it.

These experiments were taken up in later years by Mitchell (1908) and by Hooper (1923), with similar results, and no subsequent studies impugned the validity of the observations or the method, although there is evidence that these early studies were misunderstood (Wolberg, 1948; Le Cron & Bordeaux, 1949). The connection to the present experiments is evident—keeping track of minutes without the aid of a clock is equivalent to synchronizing on 00. The difference is that the hypnotic task is more difficult, since the target is a specific minute. It should be noted that Bramwell's experiments were not designed to study time estimation while under hypnosis, which has been shown elsewhere to be no more accurate than in the waking state (Stalnaker & Richardson, 1930), but instead were directed towards an investigation of unconscious timekeeping. It is certainly true that experimental protocols in 90-year-old studies should be questioned, but it is still important to recognize that the present experiments are not without precedent. The range of unconscious cognitive processes, including hypnotic effects, has recently been discussed by Kihlstrom (1987).

In a recent book by Richard Feynman (1988), the author describes how he and John Tukey, as graduate students, discovered that the process of counting can be extremely precise (pp. 53–59). Feynman found that counting silently to 60 always took him 48 seconds, and that in attempting to distract himself from counting by performing other tasks simultaneously, he observed that under almost all circumstances that he could devise, including reading, the period remained invariant. Paying less and less attention to the counting did not degrade the ability to keep time.

This relates to the current studies in an obvious manner. An extension of the ability described by Feynman would be the ability to count without being aware of it, which is exactly what is required for the present experiments to be successful. The subjects of Bramwell (1900), when asked to explain under hypnosis how they were able to keep track of the time with such accuracy, said that they counted seconds continuously. There is also at least one case of an autistic child with a phenomenal timekeeping sense whose attention was always directed towards counting (Rothenberg, 1977, p. 225).

Conclusions

The principal conclusion of this study is that there is a capacity to recognize location in the time domain with great precision. These passive time estimation studies indicate that the internal timekeeper will adjust its frequency to whatever fixed-frequency source is available. Once the timekeeper has been entrained to a source, a phase change will break the entrainment, and several days are needed to reestablish synchronization.

There may or may not be limits to the periods that can be tracked; the present investigation has shown that two periods around 60 seconds can be followed with an averaged precision on the order of one part in 10^4. The manifestation of the effect is particularly remarkable in that it suggests that the timekeeper, operating at an unconscious level, periodically stimulates the conscious mind to provide calibration information, and that, for the two subjects investigated, 20–30% of watch-consulting decisions are timekeeper-triggered.

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